PDR dynamics from pv-diagrams

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Bonn, October 19, 2012

What do we expect?

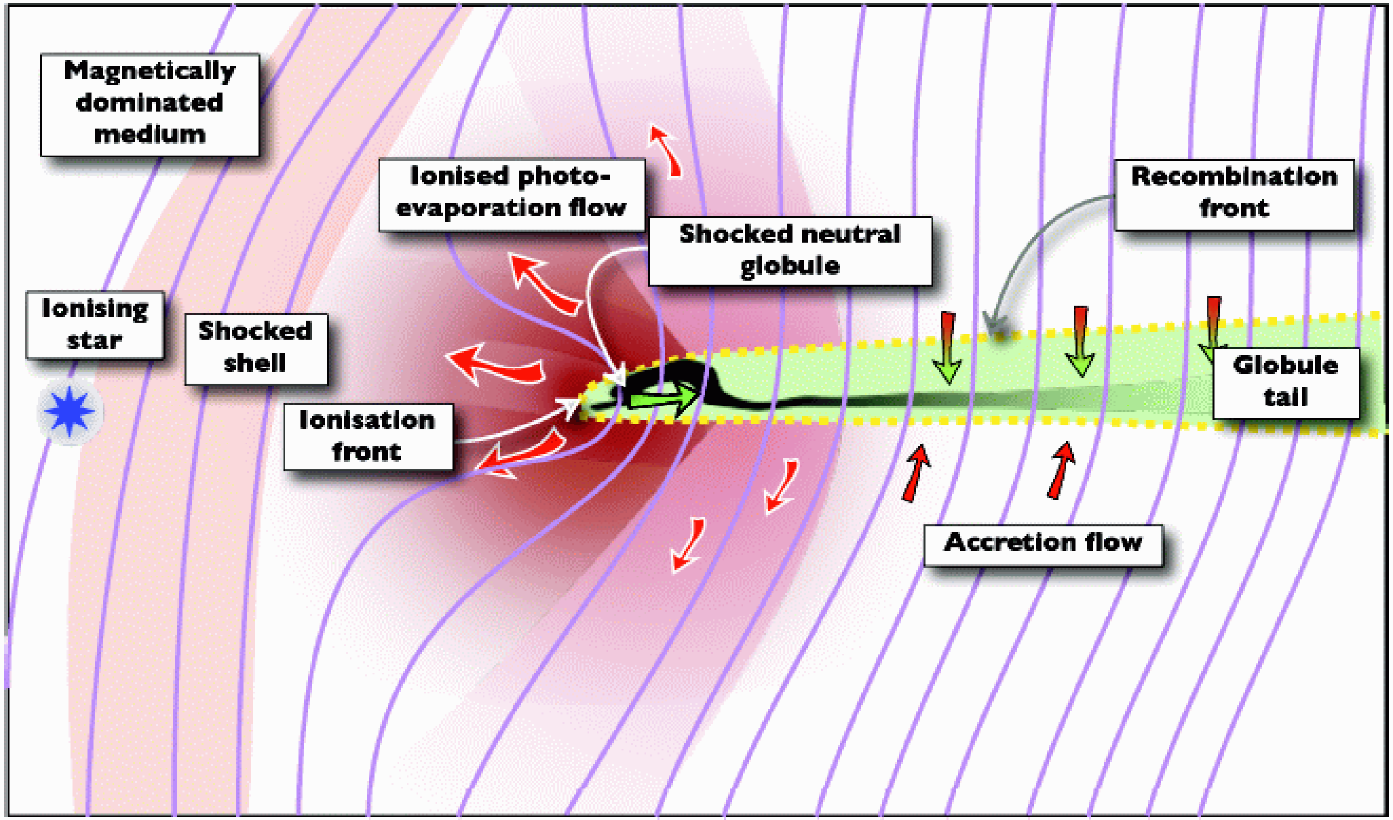
Dynamics and kinematics:

- Photo-evaporation of PDRs dominates flow of ionized material
- High pressure zone at PDR surface → cloud compression

  → shock fronts
- Ionization front "eats" into molecular cloud

→ **pillar formation**

- Advection flows
- Unknown impact of turbulence



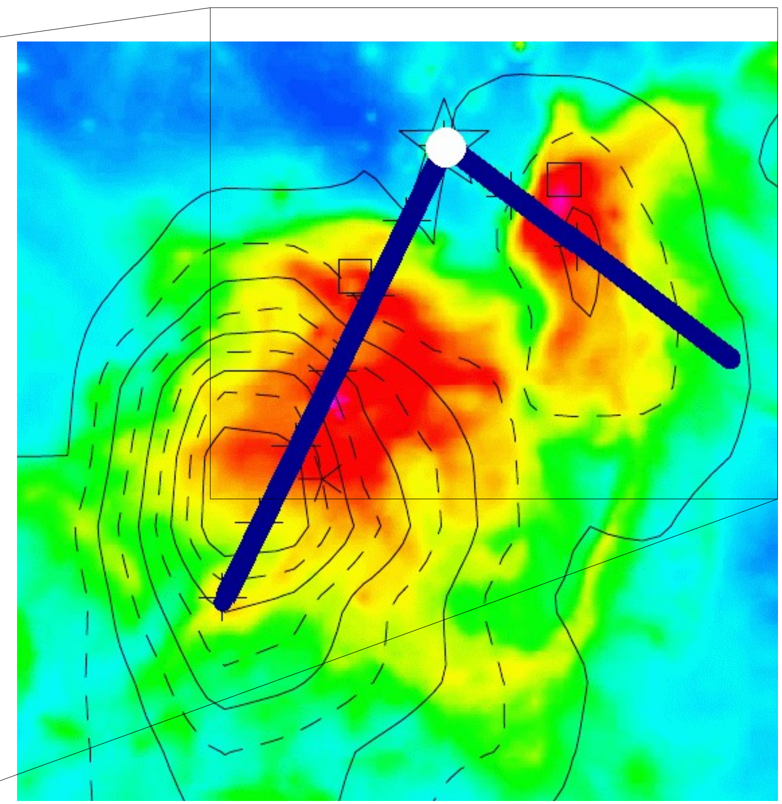
3-D MHD model by Henney et al. (2009)

HIFI Observations

Measure layering structure - example: NGC3603

- cuts across the interfaces of PDRs and shock regions
- deep integrations at selected positions for rare species

Pillars at PDR fronts (HST, Brandner et al. 2000)



Observed cuts overlaid on Spitzer 8µm (color) and CO 4-3 (contours)

Results

Summary of the HIFI mapping data. Numbers give the peak T_A^* in Kelvin for the considered stripe and transition.

species	[CII]	CO	^{13}CO	HCO^+	CH	CH^+	C_2H	H_2O	H_2O
frequency [GHz]	1901	1037	1101	535	537	835	524	1113	557
NGC3603 MM1	40.4	12.8	2.61	0.56	0.48	0.64[a]	0.39	0.43	0.46
NGC3603 MM2	44.0	11.3	2.69	0.47	0.51	0.60[a]	0.30	0.39	0.45
MonR2	62.7	32.8	10.4	4.55	1.10	1.31	1.04	1.05	1.04
S140	23.8	25.9	7.71	7.44	0.69	0.39[a,r]	0.89	2.55	2.54
Carina N	63.6	16.3	3.19	0.89	0.80	<0.1[a]	0.46	<0.15	0.16[a]
Carina S	9.82	3.48	<0.1	0.09	<0.05	<0.1[a]	<0.03	<0.15	<0.02[a]
NGC7023 N	33.6	19.9	3.46	0.27	0.71	0.37	0.11	<0.15	0.12[a]
NGC7023 C	33.1	14	-	0.27	0.7	-	0.11	-	0.12[a]
NGC7023 E	13.8	3.93	<0.1	<0.07	0.09[m]	<0.03[a]	<0.05	<0.1	<0.02[a]
Rosette N	5.92	2.36	<0.3	0.14	0.18	<0.07[a]	<0.07	<0.3	<0.03[a]
Rosette S	5.3	<0.5	<0.3	<0.03	<0.1	<0.07[a]	<0.07	<0.3	0.04[a]
Horsehead	13.5	2.62	-	0.16	0.26	<0.1[a]	<0.03	-	0.09[a]
Ced 201	5.82	<0.15[a]	<0.03[a]	<0.03[a]	<0.03[a]	<0.15[a]	<0.03[a]	<0.03[a]	0.02[a,m]

species	H_2CO	CS	SO	SH^+	NH_3	N_2H^+
frequency [GHz]	526	539	560	526	572	559
NGC3603 MM1	<0.06	0.08	<0.1	<0.07	0.13	<0.07
NGC3603 MM2	<0.07	0.09[m]	<0.1	<0.07	0.13	<0.1
MonR2	0.31	0.38	0.31	<0.03	1.02	1.21
S140	0.52	0.36	0.42	<0.03	1.75	1.44
Carina N	0.10	0.08	<0.02[a]	0.07[m]	0.08[a]	<0.02[a]
Carina S	<0.03	<0.03	<0.02[a]	<0.03	<0.02[a]	<0.02[a]
NGC7023 N	<0.03	<0.03	<0.03[a]	0.08	0.05[a]	<0.03[a]
NGC7023 C	<0.03	<0.03	<0.03[a]	0.06	0.05[a]	<0.03[a]
NGC7023 E	<0.03	0.05[m]	<0.02[a]	<0.05	<0.02[a]	<0.02[a]
Rosette N	<0.07	<0.03	<0.03[a]	<0.05	<0.03[a]	<0.03[a]
Rosette S	<0.07	<0.07	<0.03[a]	<0.05	<0.03[a]	<0.03[a]
Horsehead	<0.02	<0.02	<0.01	<0.02	0.02	0.01[a,m]
Ced 201	<0.03[a]	<0.03[a]	<0.02[a]	<0.03[a]	<0.02[a]	<0.02[a]

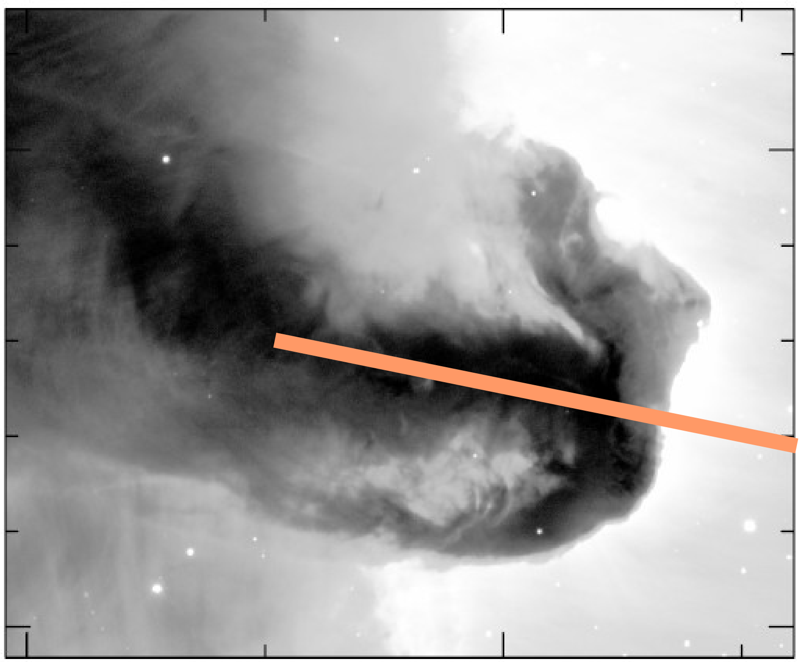
(a) Only single point on stripe observed, no OTF map.

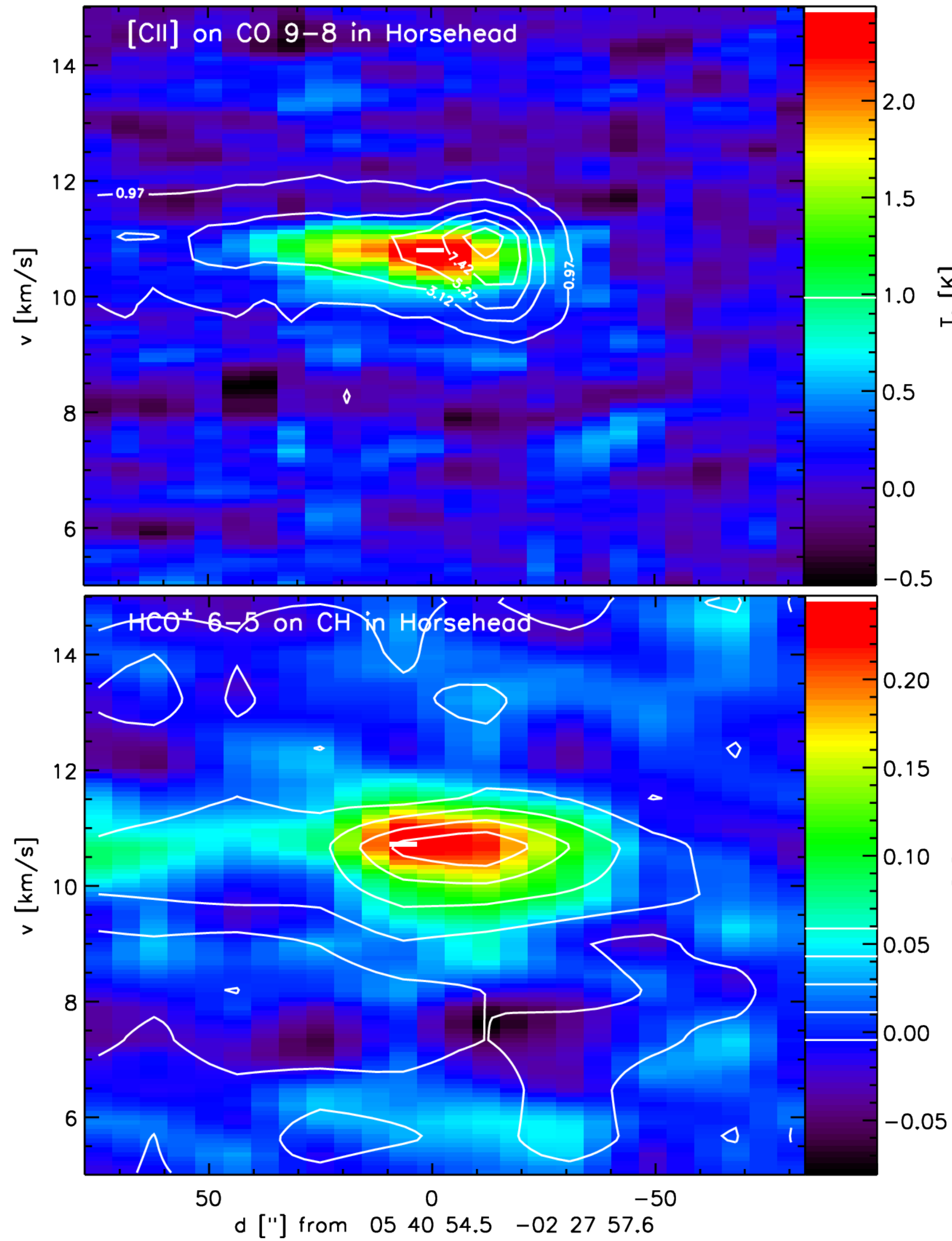
(m) Marginal/tentative detection.

(r) Emission above absorption trunk of 0.27 K.

Example 1: Horsehead

Measure layering structure – **p-v diagrams**:

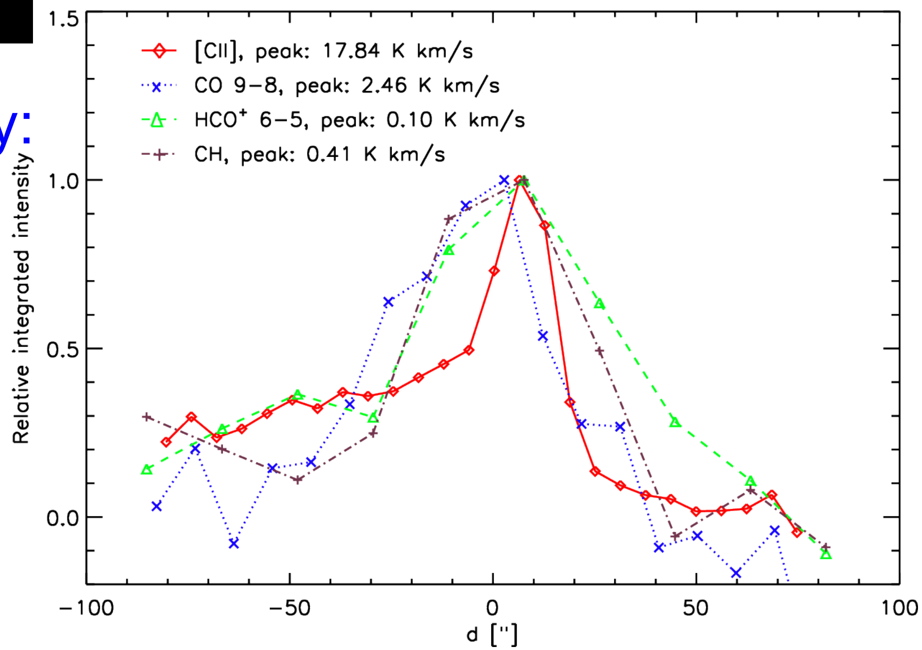




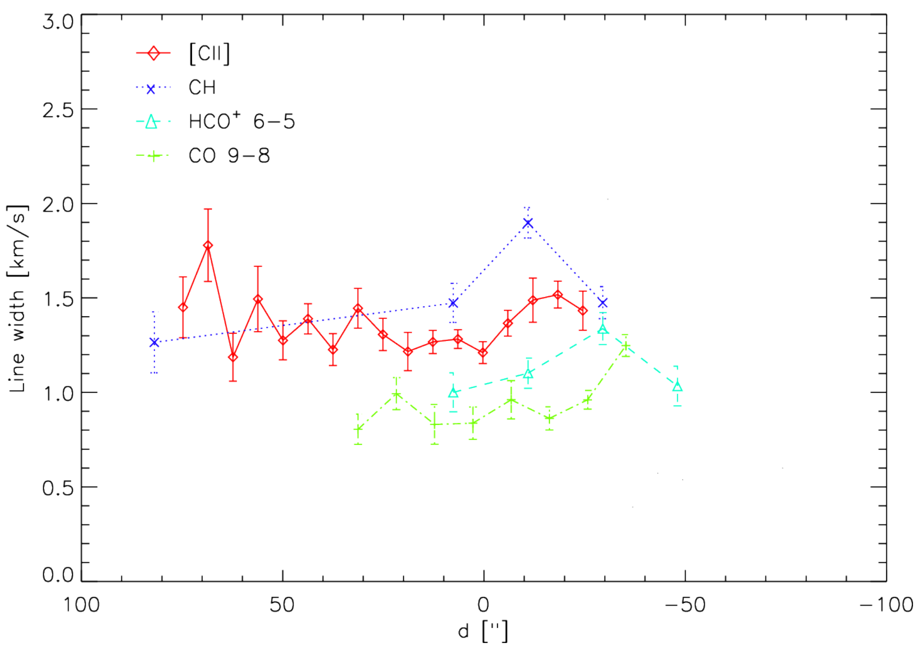
p-v diagrams reveal details of the PDR layering including the dynamical structure

Interpret line parameters

Intensity:



Width:



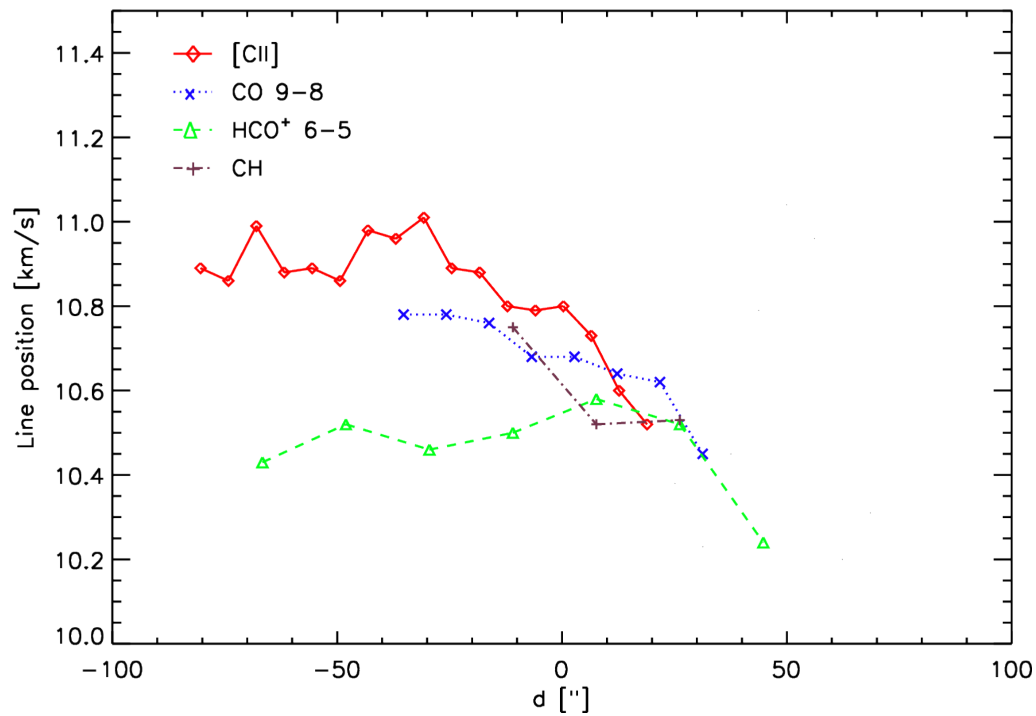
- Stratified chemical structure
- Layering $C^+ \rightarrow HCO^+ \rightarrow CO$
- CH very extended
- C^+ in sharp surface layer

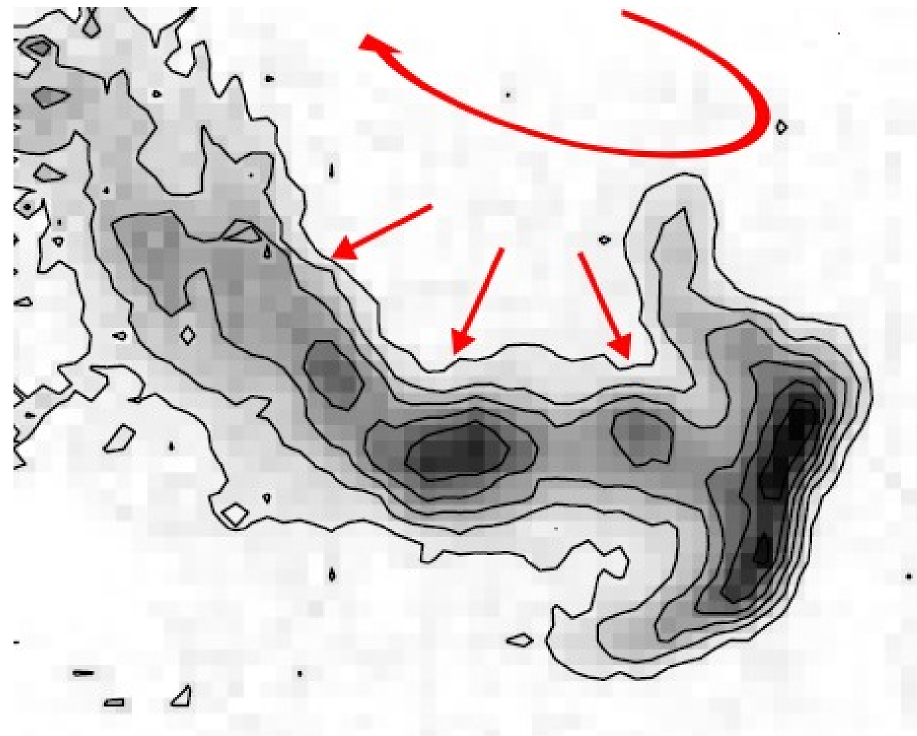
- Confirmation of expected pressure "jump" at interface
- [CII] wider than molecules
  - stronger coupling to radiation pressure
- Wider width of CH mysterious

No new results.

Interpret line parameters

Velocity structure from p-v diagrams:





Line center velocities:

• Gradient along the neck

• Offset between [CII] and high-density tracers

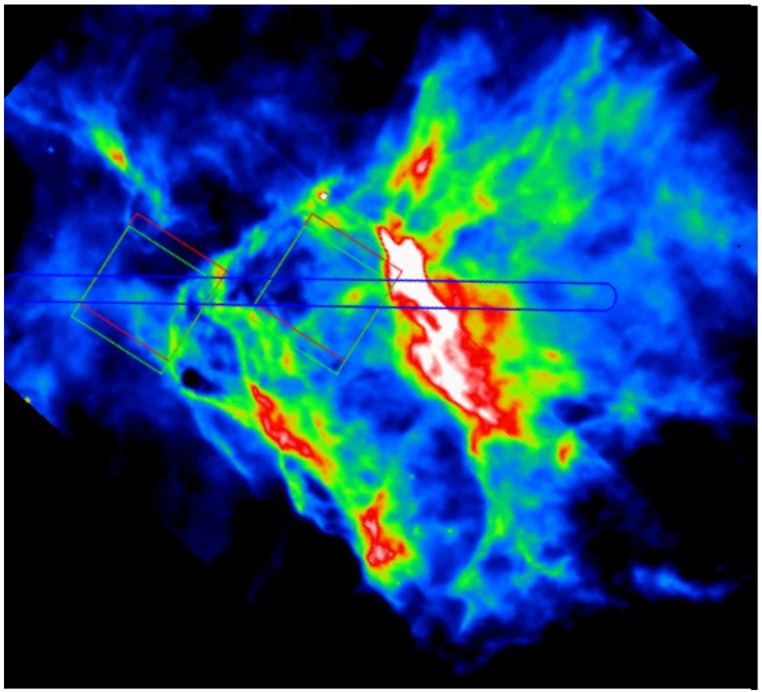
Consistent with dynamical picture of Hily-Blant et al. (2005):

• Rotation of large-scale structure

• C^+ accelerated by radiation pressure

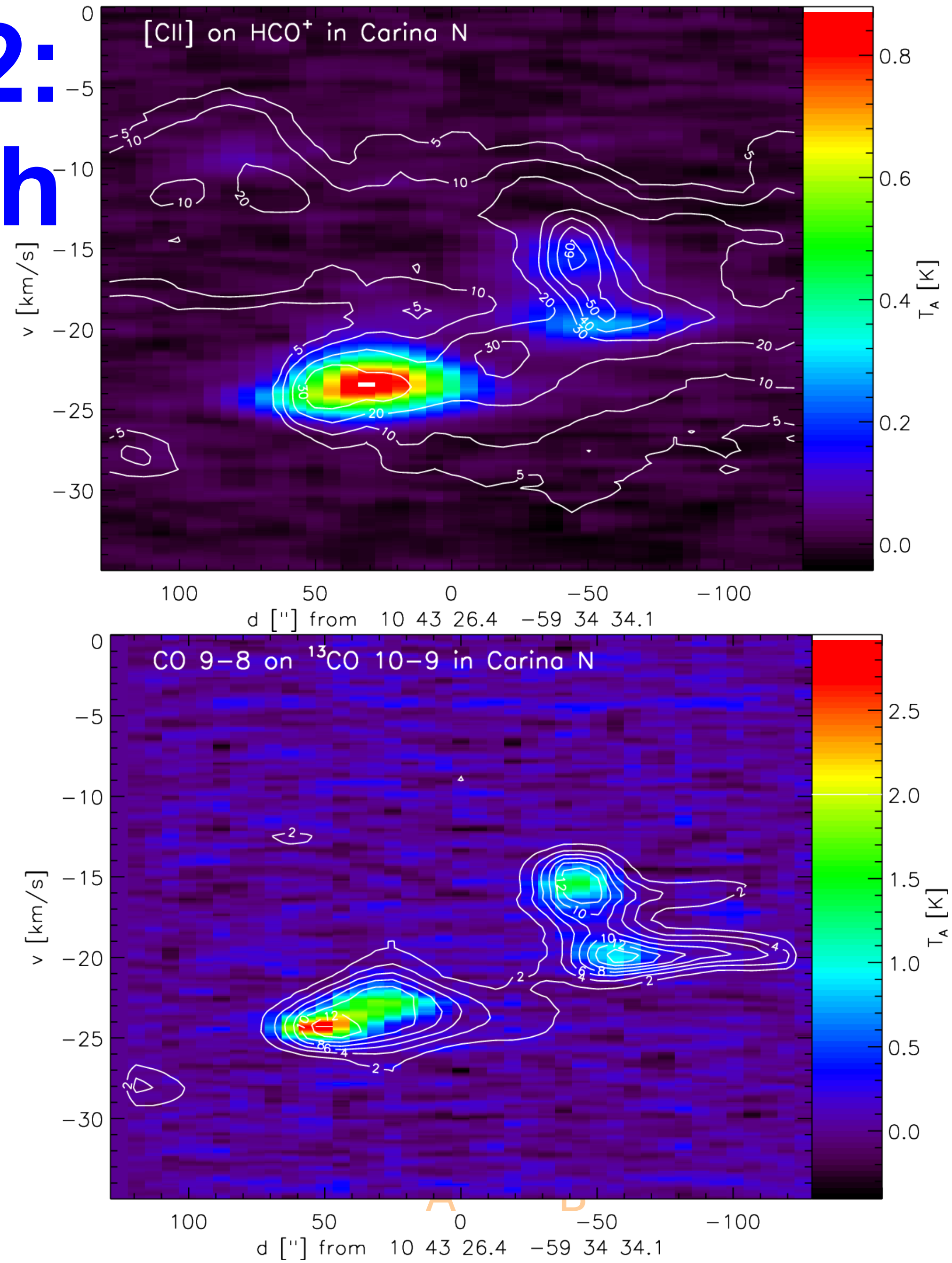
Example 2: Carina North

Multiple interfaces:



Cut through Carina North PDR

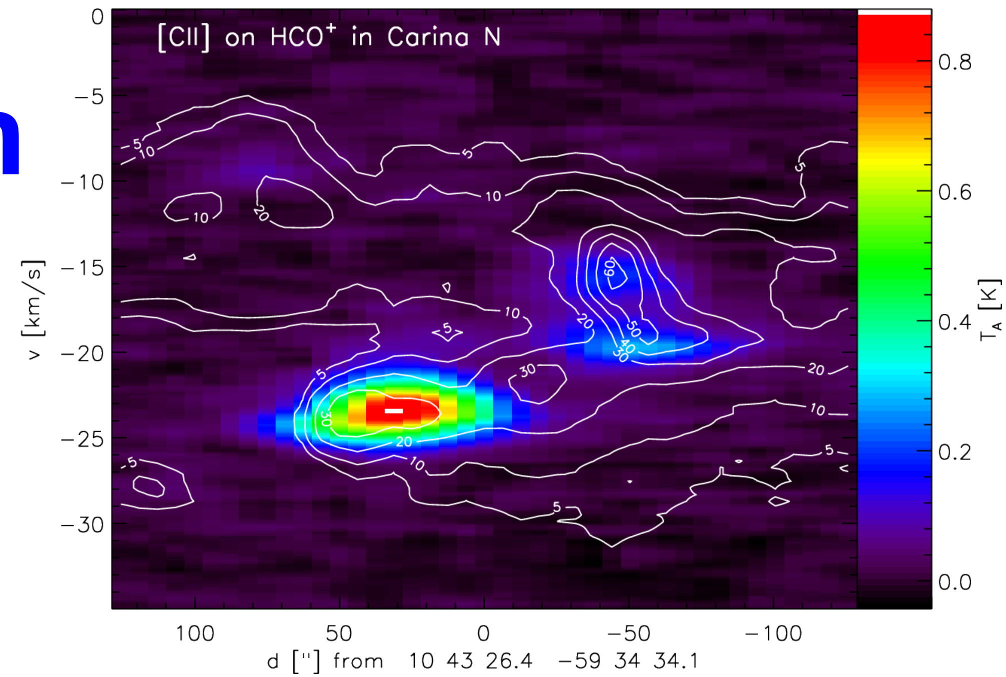
- Very difficult to interpret due to multiple components
- New data for HCO^+, C_2H, CH, SH^+, H_2CO

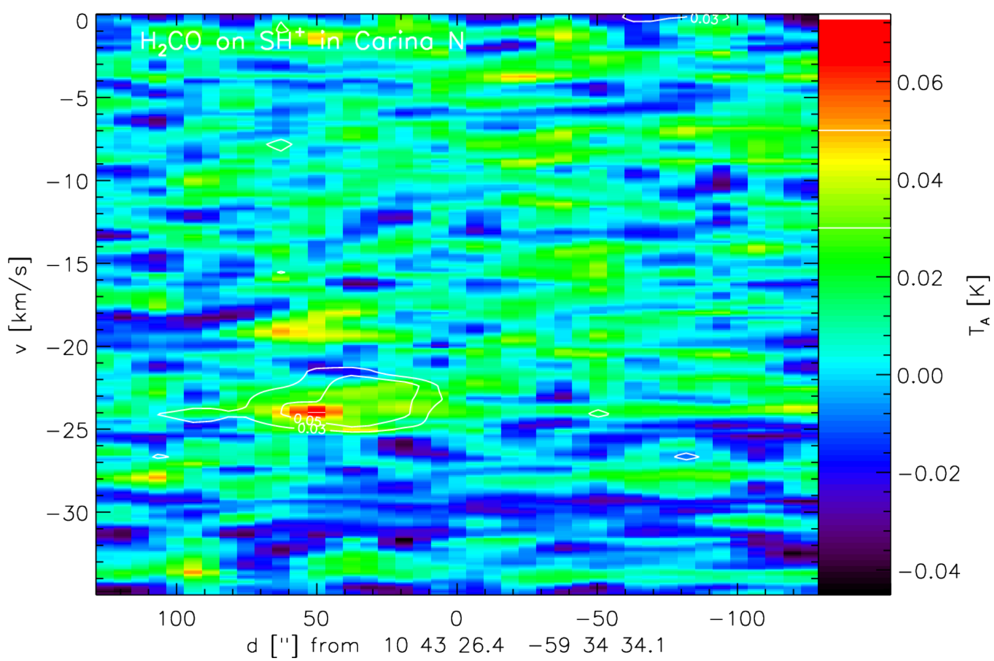


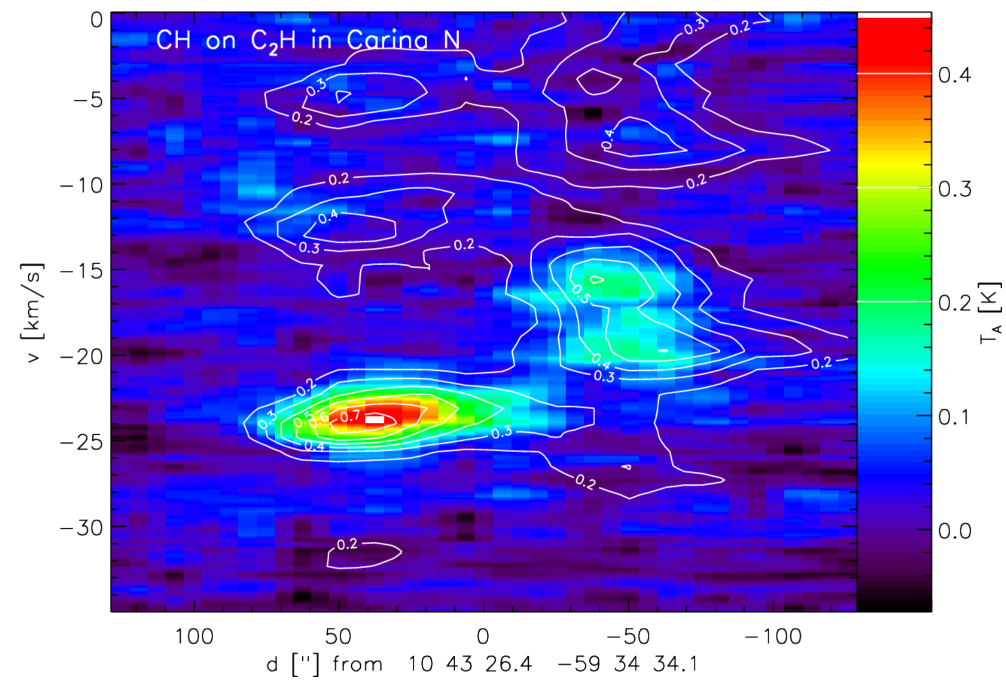
Top: [CII] (contour) and HCO^+ 6-5 (color)
Bottom: CO 9-8 (contour) ^{13}CO 10-9 (color)

Carina North

New observations provide detections of H_2CO, SH^+, C_2H





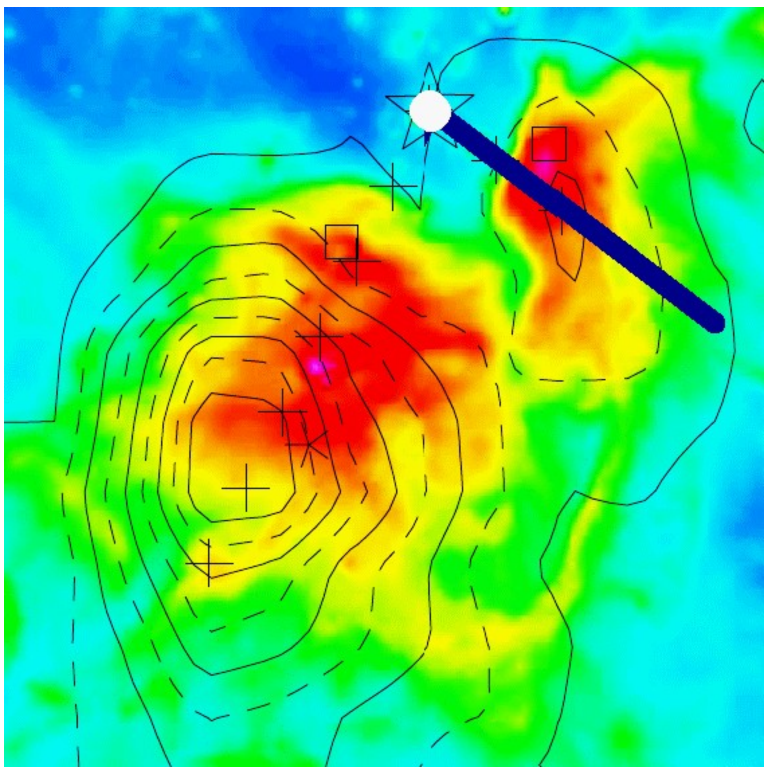


SH^+ (colors) + H_2CO (contours).

Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: C_2H (colors) + CH (contours)

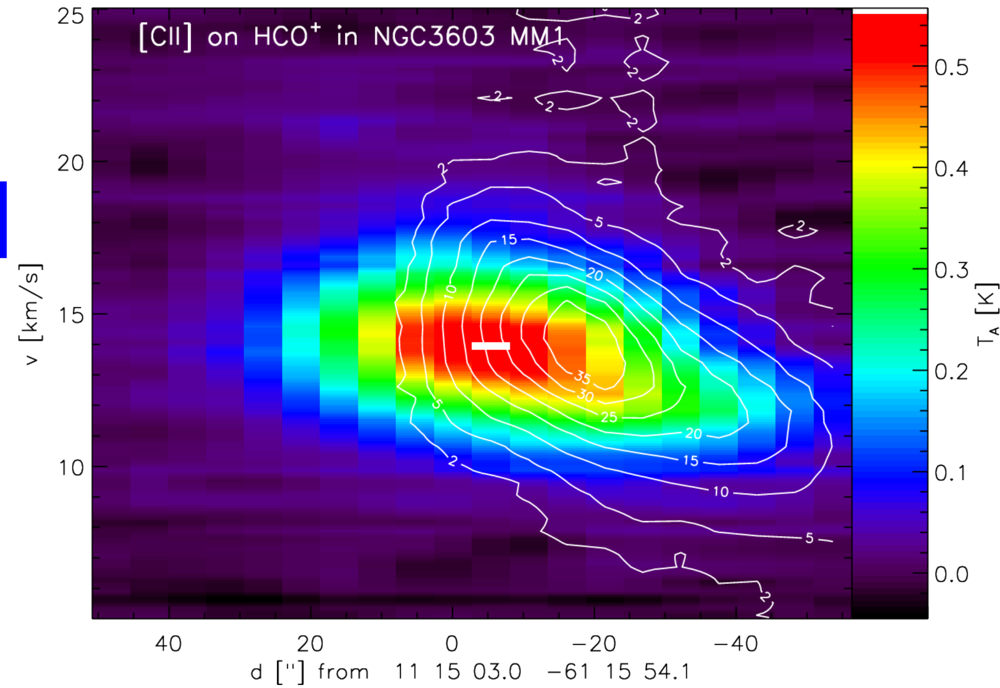
Example 3: NGC3603 MM1

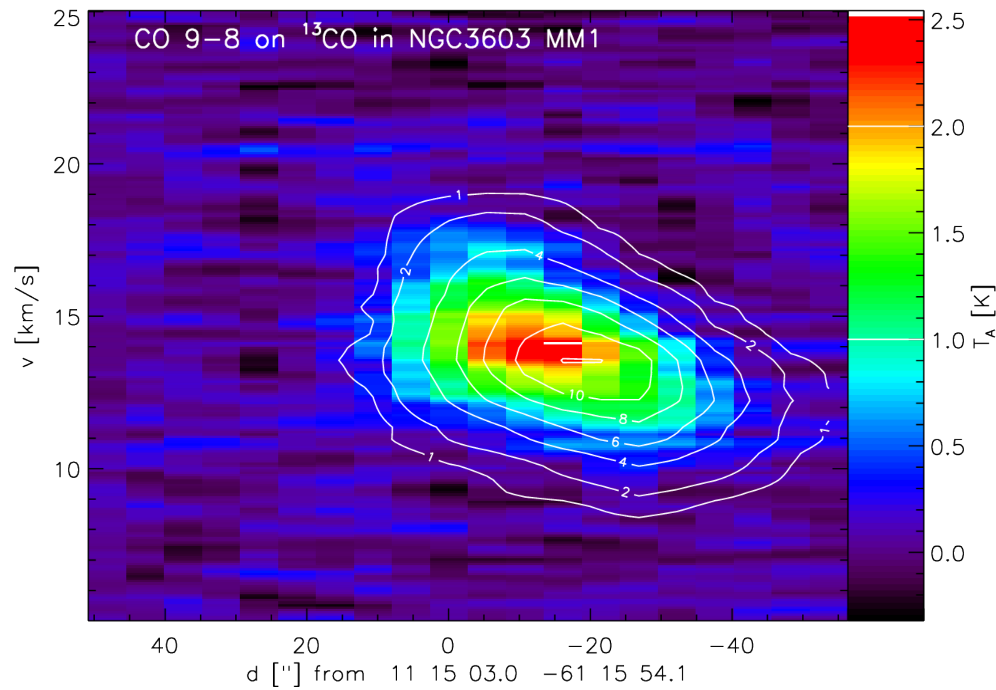
Velocity structure from p-v diagrams:



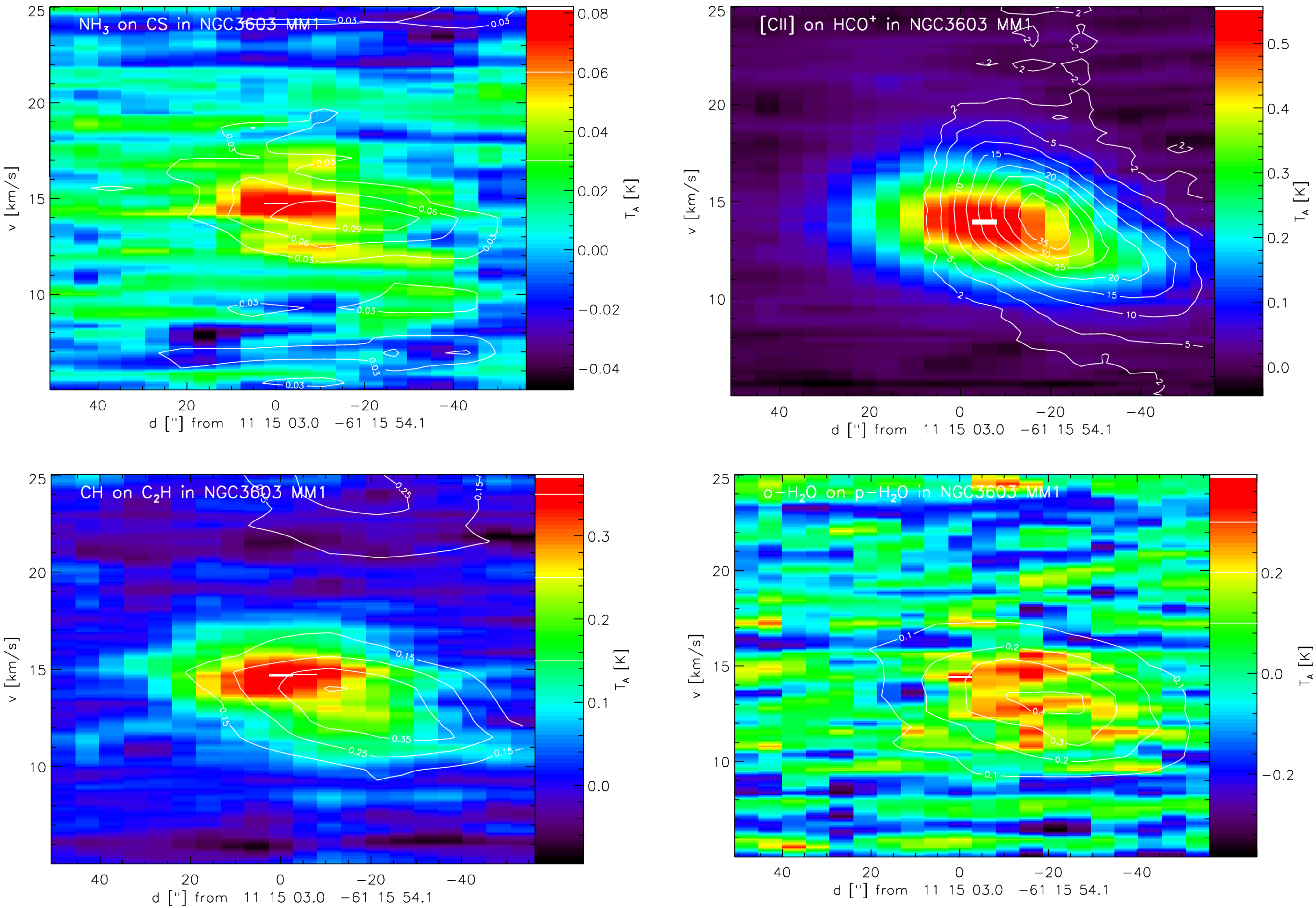
Observed cuts in NGC3603 overlaid on Spitzer 8μm

Velocity gradient across the core





p-v diagrams:
Top: HCO+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours).

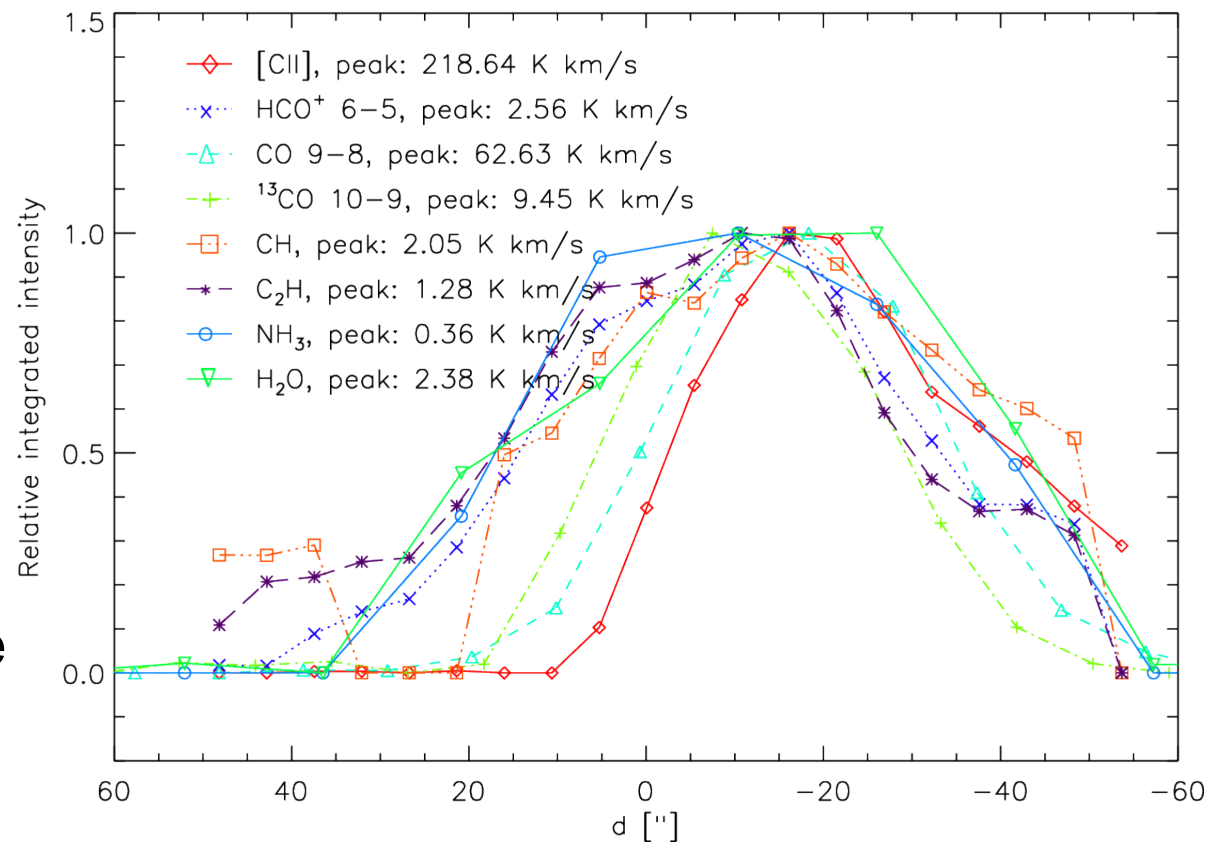


Top: CS 10-9 (colors) + NH_3 (contours).
Bottom: C_2H (colors) + CH (contours)

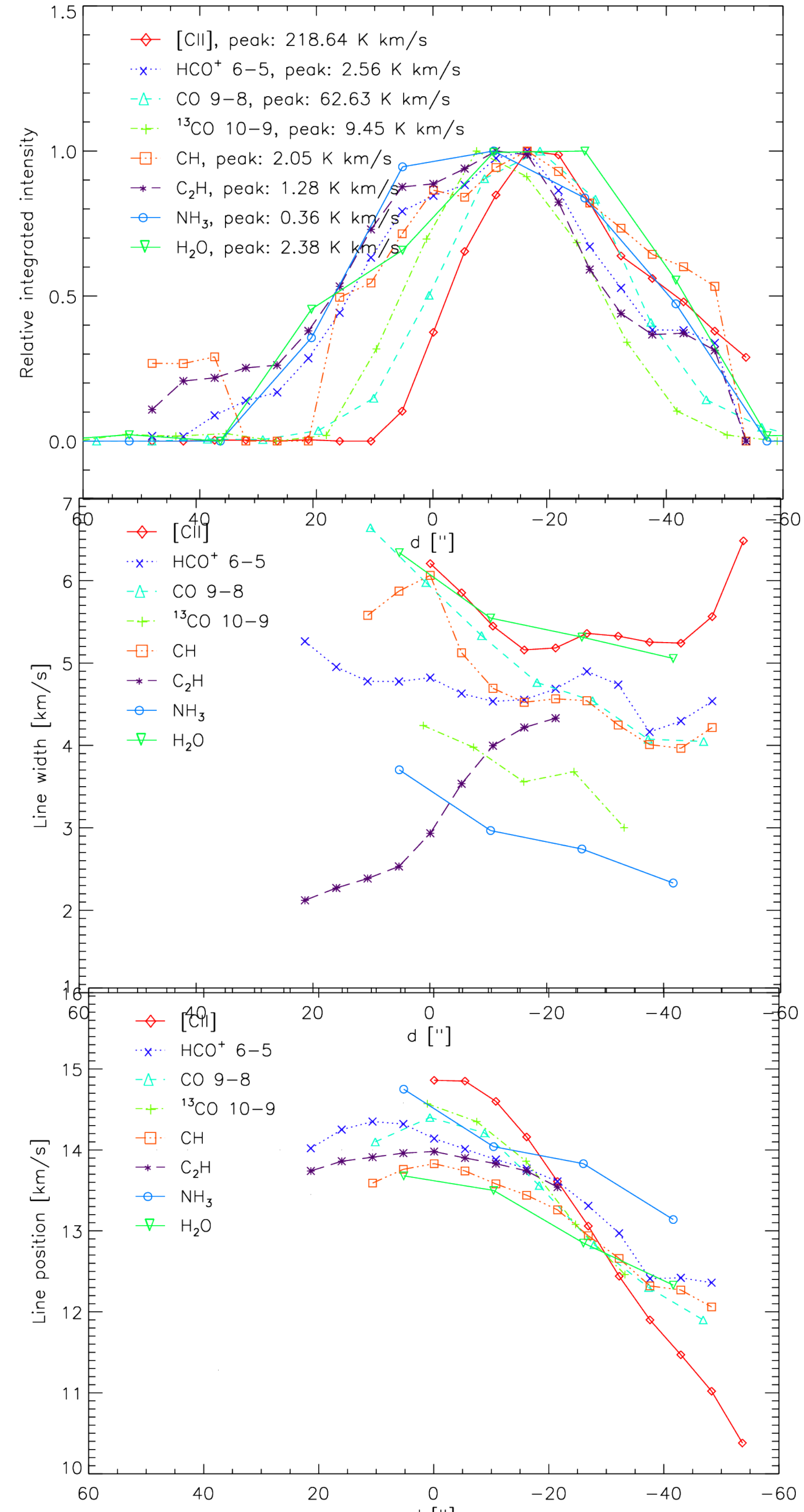
Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: p-H_2O (colors) + o-H_2O (contours)

NGC3603 MM1

- Chemical layering partially inverted!
  - [CII] peaks deeper in the core than all molecules
  - CO slightly deeper than ^{13}CO
- CH again very extended
- Tail of [CII] “behind” the core



NGC3603 MM1



Line position and width:

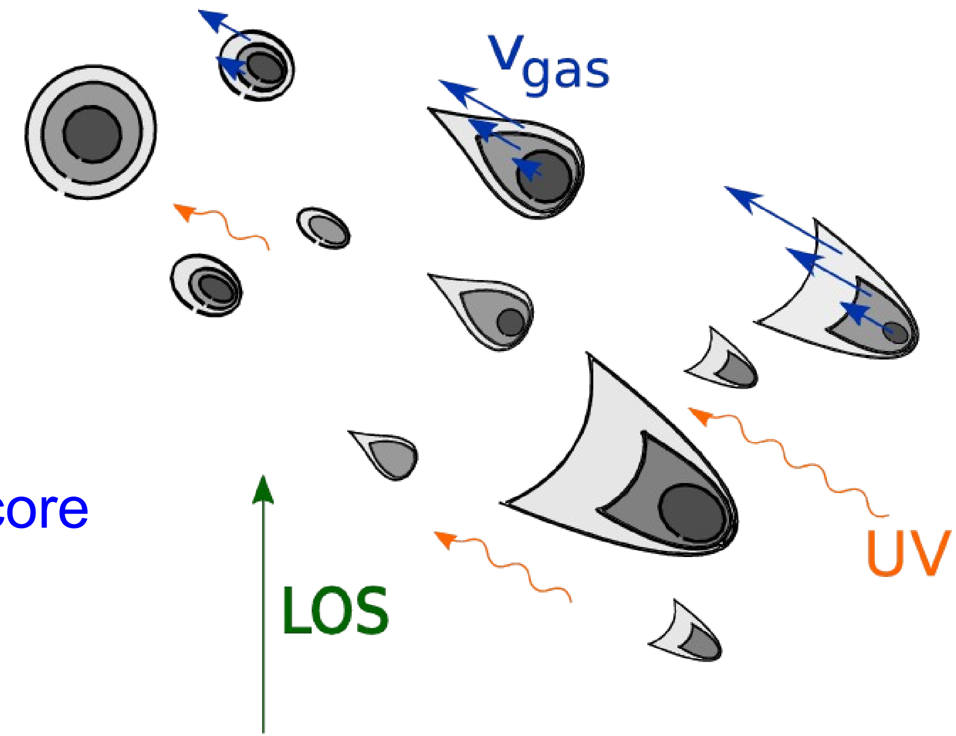
- Broadening of most lines at surface
- [CII] is red-shifted relative to molecular tracers at interface
- Stronger velocity gradient in [CII] than in molecules
- Long turbulent [CII] tail of material "behind" the core

→ C^+ must be blown from the surface into a clumpy medium

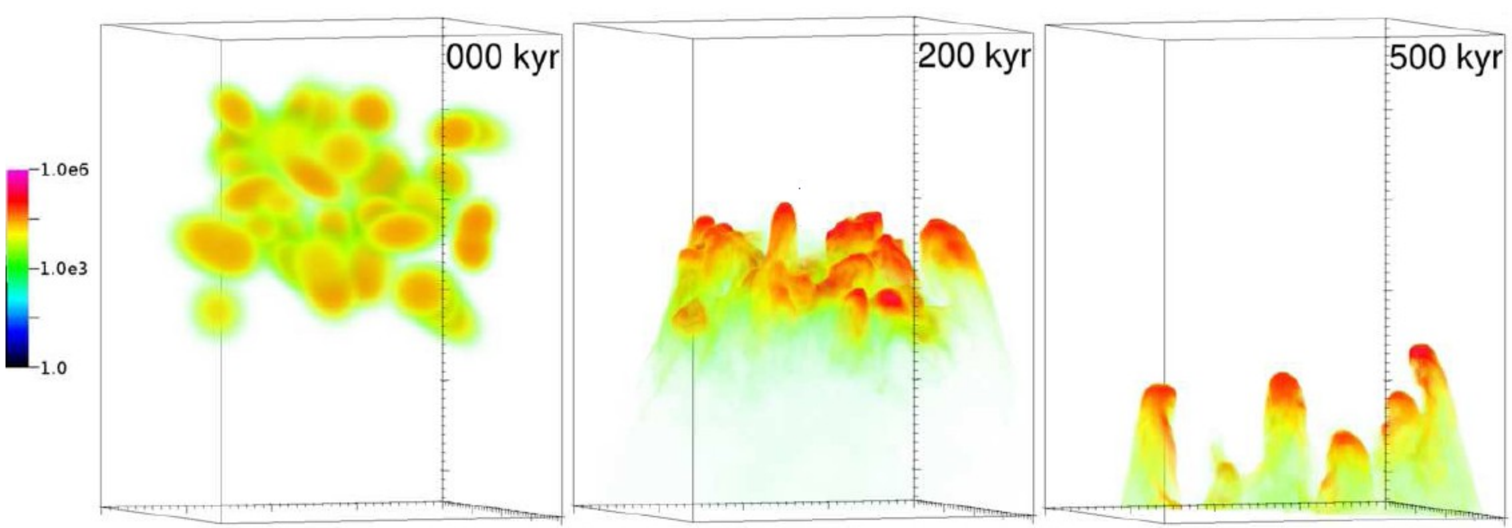
- ➔ Redshifted profiles → affected material sits behind the cluster
- ➔ The gradient along the core measures radiative (?) compression!

Interpretation

- Clumps → cometary clumps
- Evaporation flow towards cluster suppressed
- Material is “blown” into the cloud
- Compression and dispersion of the core



Compare: Mackey & Lim (MNRAS submitted)



→ **Pillar formation**

Driving mechanism

- Comparison to radiation pressure:

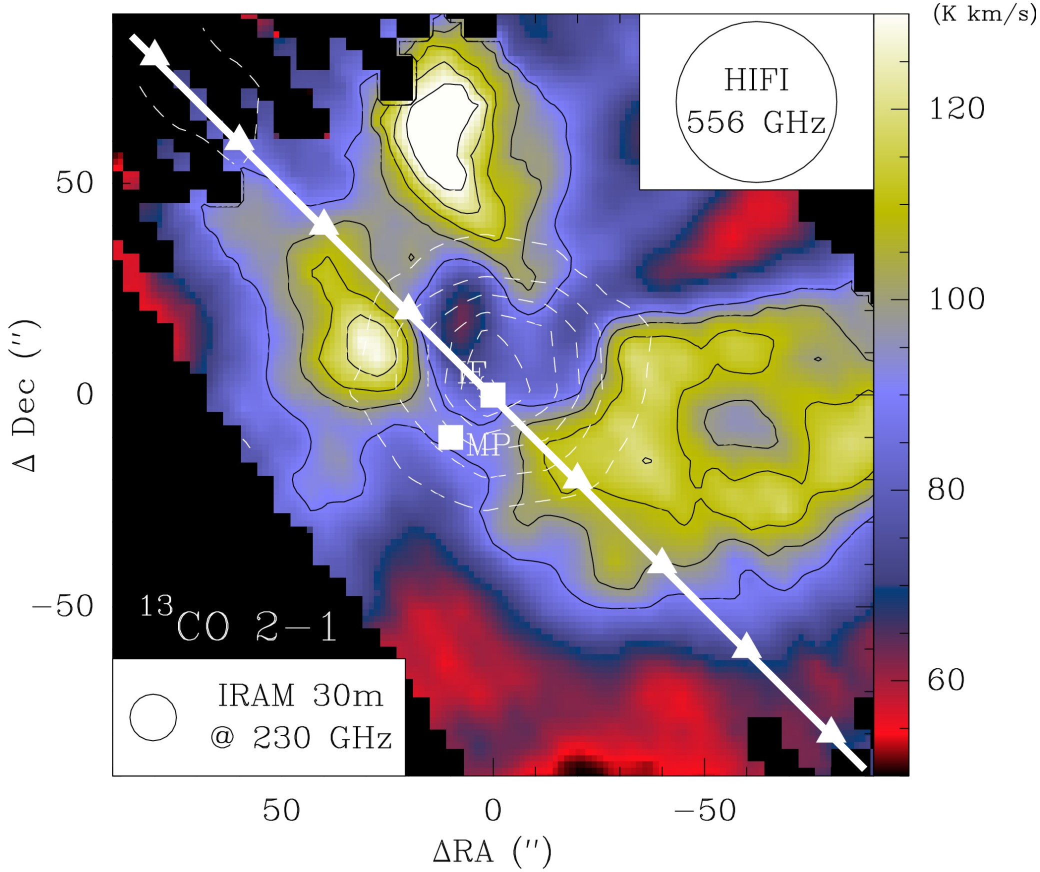
$$\chi = 2 \times 10^4 \chi_D \quad \rightarrow \quad a_{rad} = 3.2 \times 10^{17} \frac{\mathrm{km/s}}{\mathrm{a}} \times \frac{\mathrm{cm}^{-2}}{N}$$

$$N = \frac{700\ M_O}{\pi\left(0.4\mathrm{pc}\right)^2} = 1.7 \times 10^{23}\,\mathrm{cm}^{-2} \quad \rightarrow \quad v = 20\ \mathrm{km/s}\ \text{after}\ 1\mathrm{Ma}$$

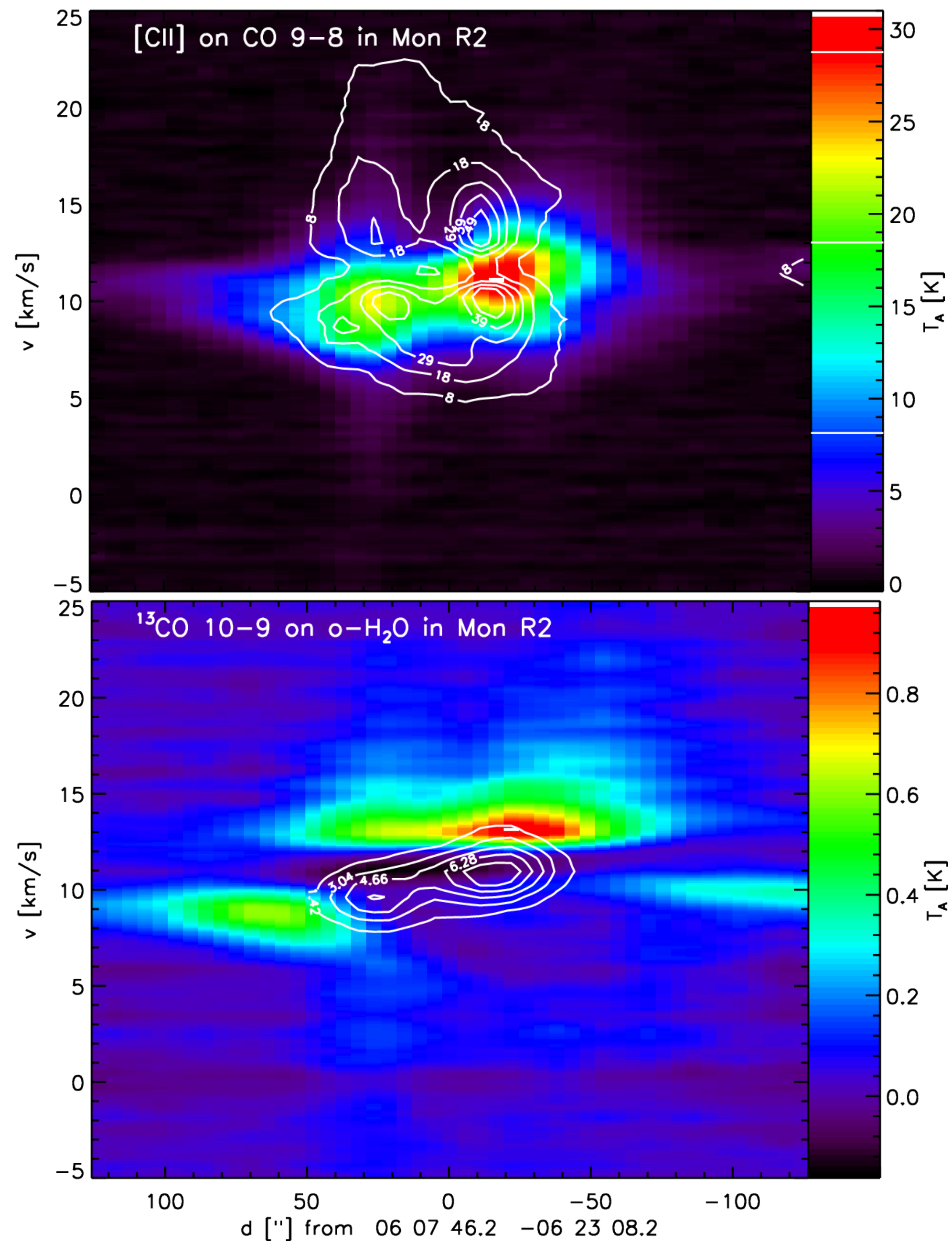
- Additional momentum must have dispersed more gas that is no longer present in the core
- Other pressure contributions only add up

- Signs evaporation flows or pressure gradient across front hidden in compression pattern

Example 4: Mon R2

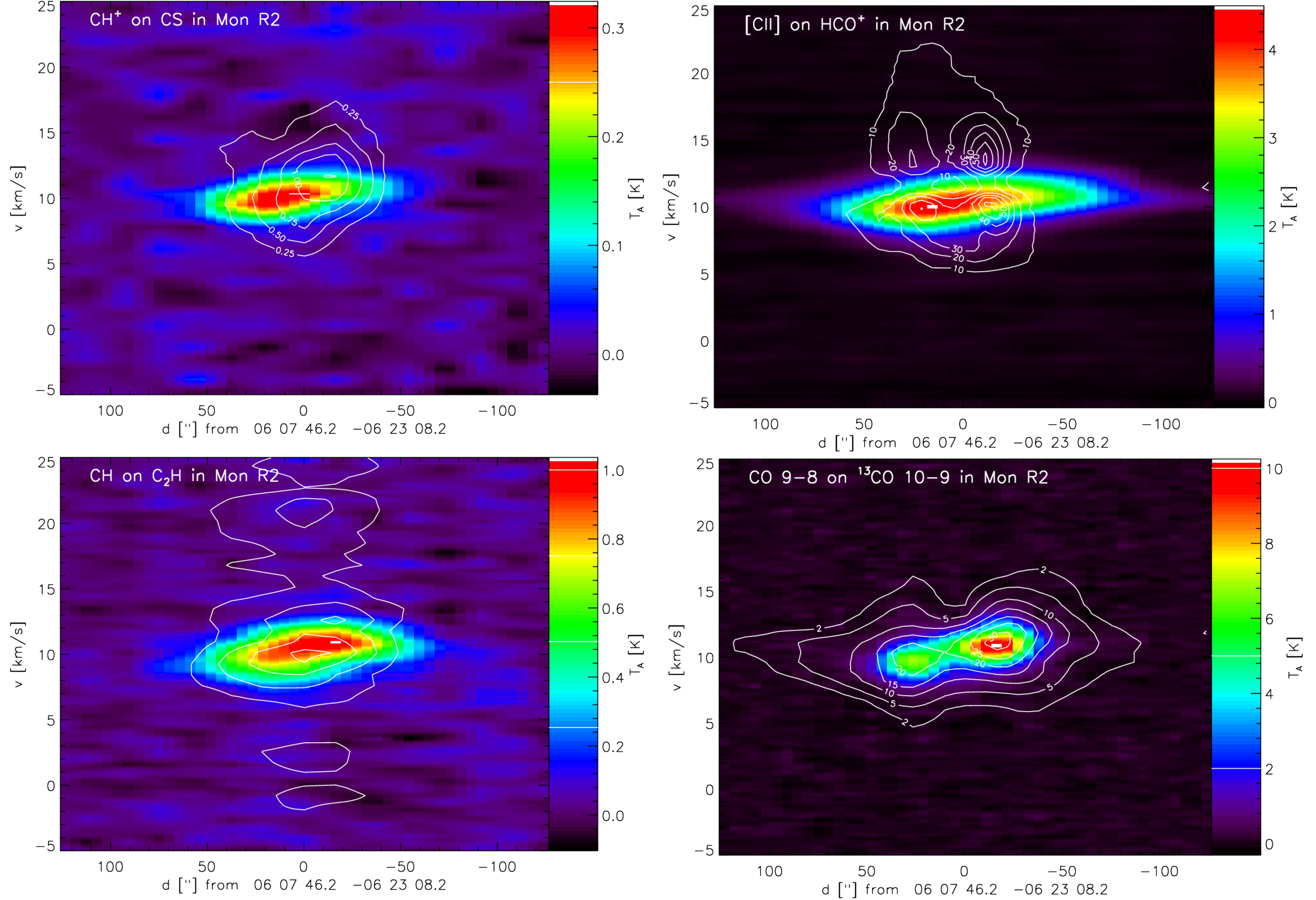


Observed cut in Mon R2 on ^{13}CO 2-1 and H recombination lines



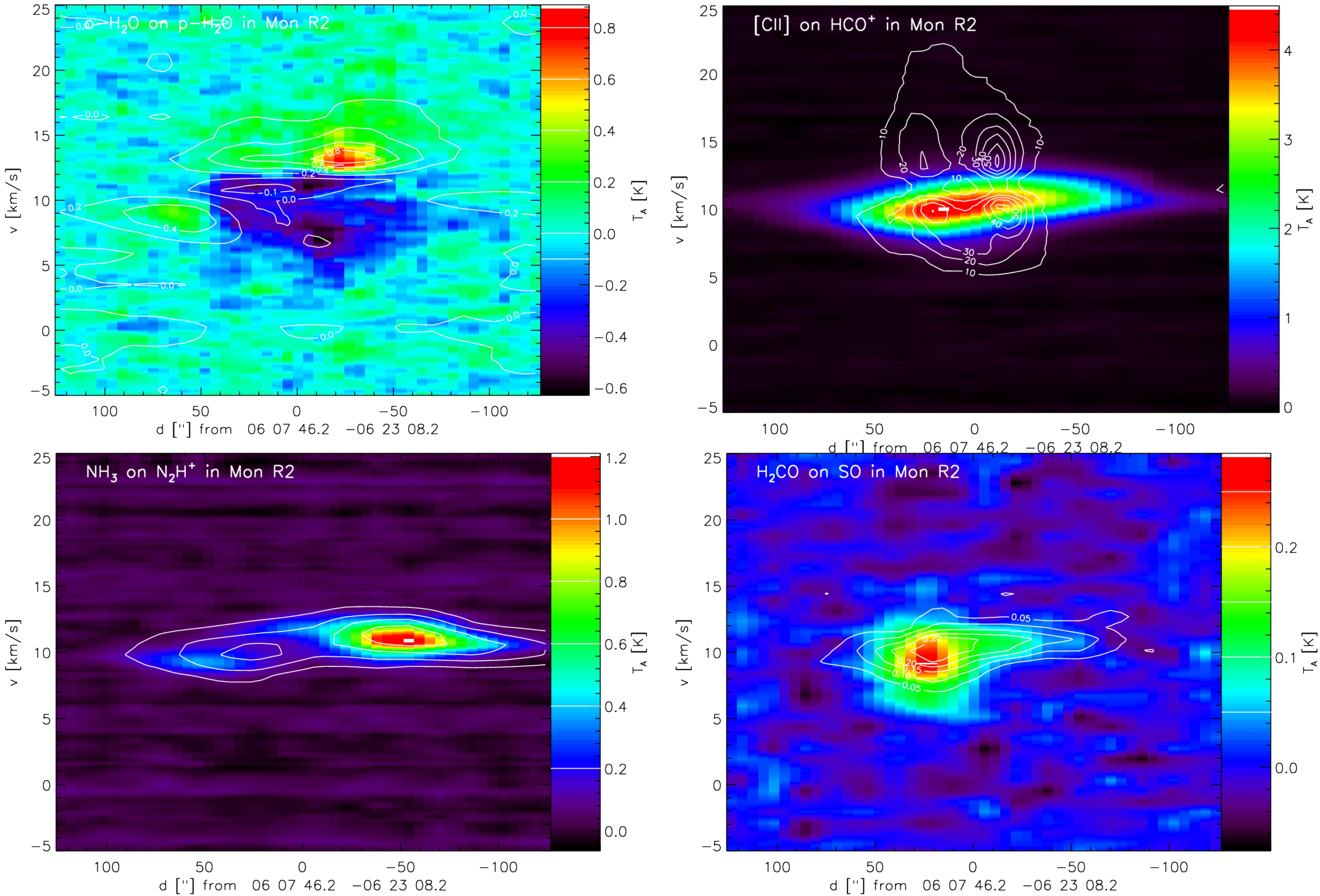
p-v diagrams:
Top: CO 9-8 (colors) + [CII] (contours).
Bottom: o-H_2O (colors) + ^{13}CO 10-9 (contours).

- Additional observation of inner region available
- Still needs to be combined with cut



Top: CS 10-9 (colors) + CH^+ (contours).
Bottom: C_2H (colors) + CH (contours)

Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours)

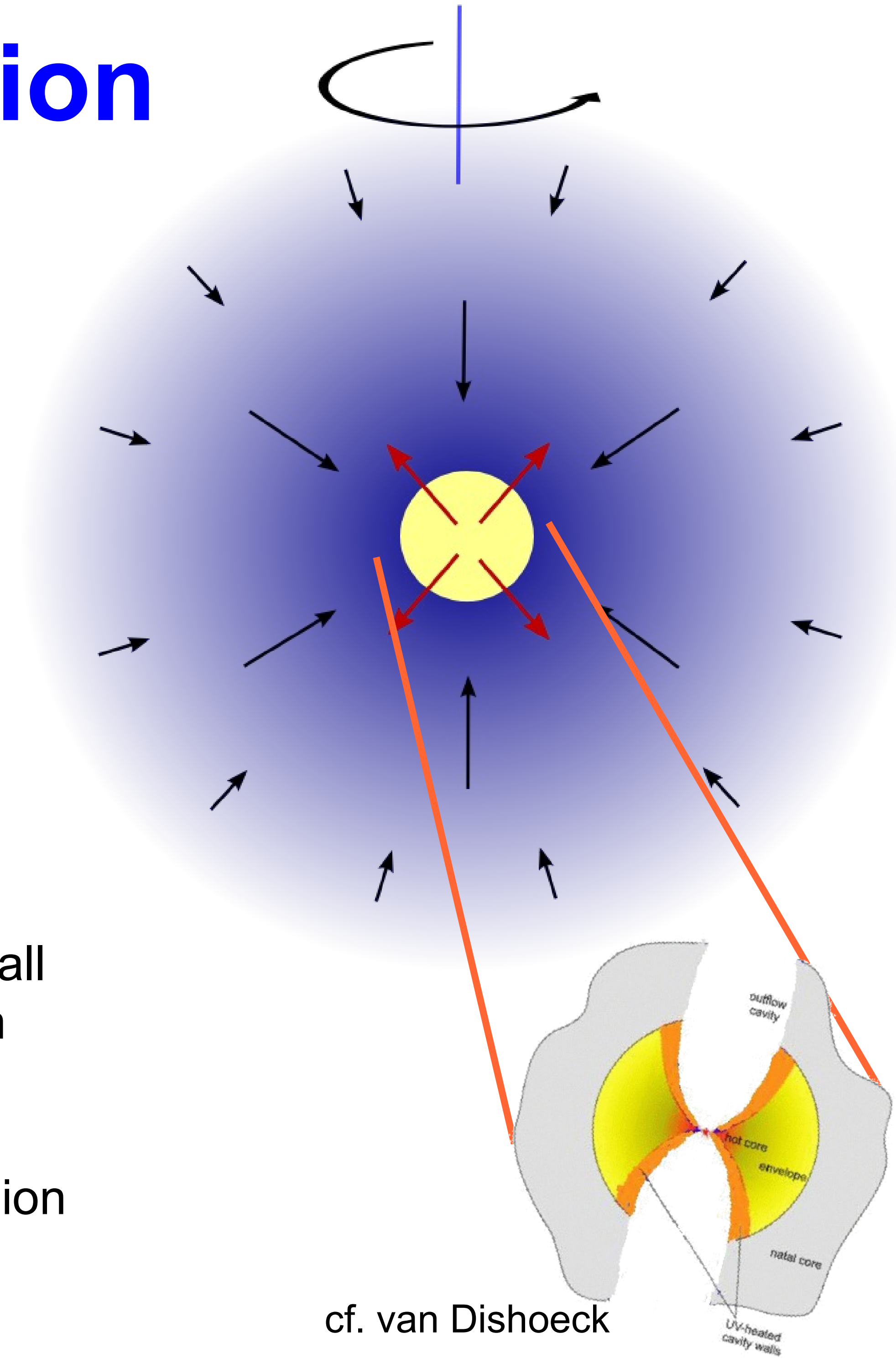


Top: p-H_2O (colors) + o-H_2O (contours). Top: HCO^+ 6-5 (colors) + [CII] (contours).

Bottom: N_2H^+ (colors) + NH_3 (contours) Bottom: SO (colors) + H_2CO (contours)

Interpretation

- Large-scale infalling cloud
  - Increasing density
  - Accelerated infall
  - Large-scale rotation
- Expanding walls of HII region
  - Harbors bipolar outflow

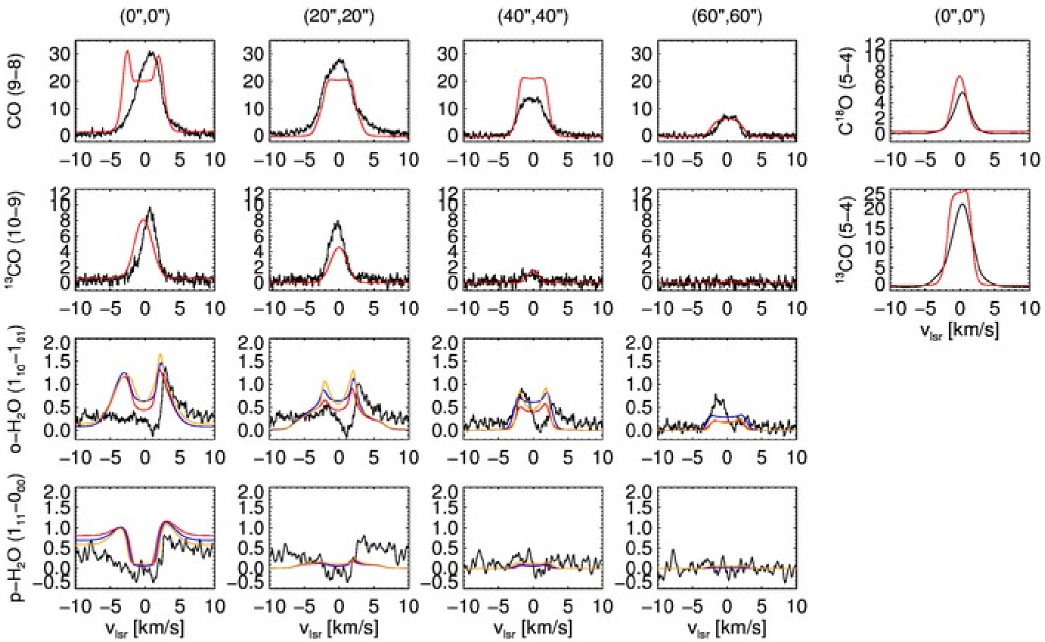


cf. van Dishoeck

- Water in absorption for low velocities, red-shifted velocities in emission
  - Emission from backside or core-infall
- Double-peaked [CII] profile mainly from walls of HII region
  - Wings trace ionized flow
  - Some self-absorption in the HII region

Multi-line model fit

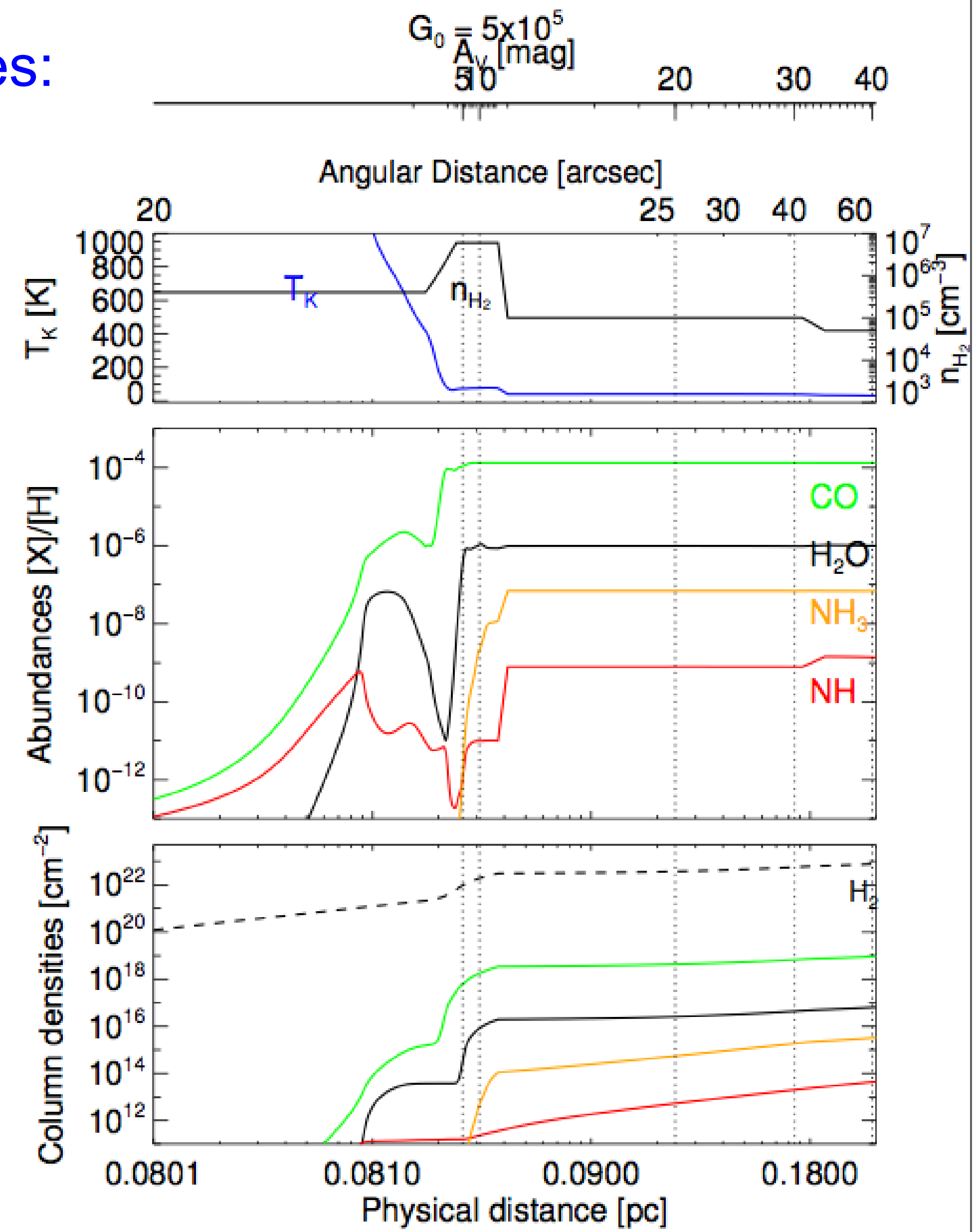
Combine HIFI and ground-based profiles:



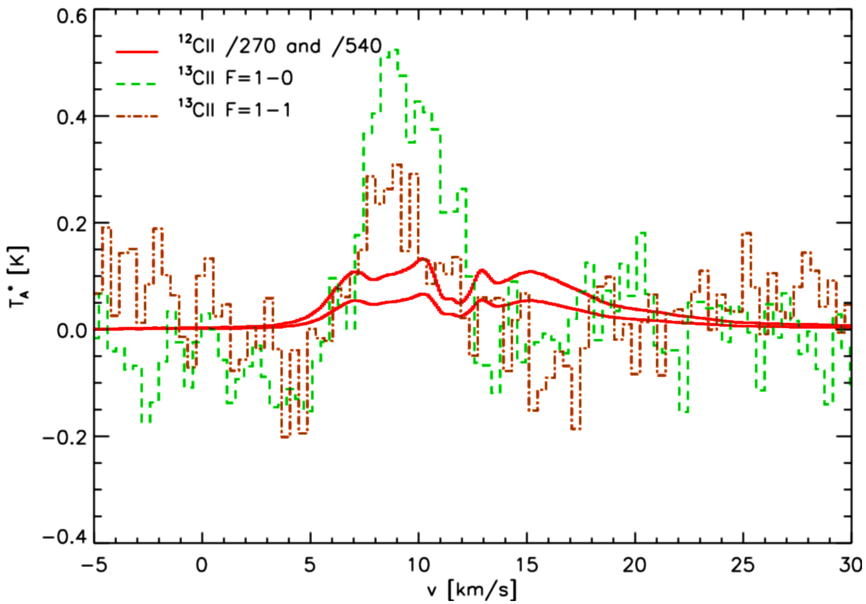
1-D PDR and radiative transfer model:

- High-velocity expanding layer:
  T > 100K, X(o-H_2O) ~ 10^{-7}
- Low-velocity cloud:
  T < 100K, X(o-H_2O) ~ 10^{-8}

Pilleri et al. (2012)

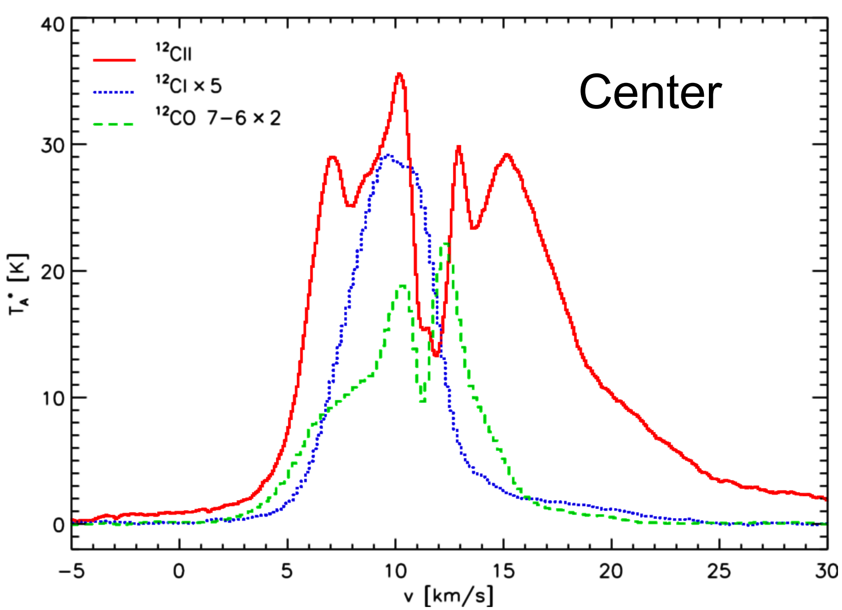


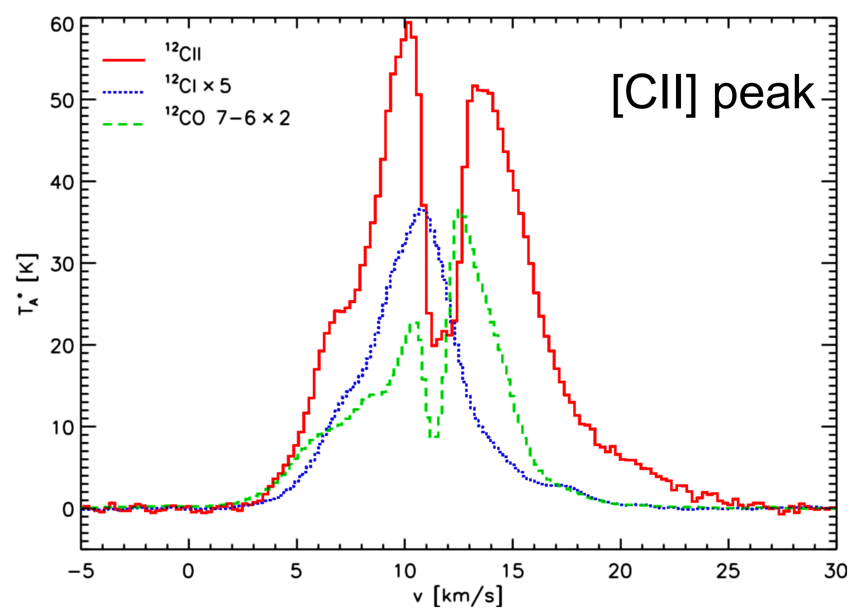
The asymmetry puzzle



- In spherically symmetric picture, central velocity at 11km/s and dip in [CII] due to self-absorption
- But red component invisible in [^{13}CII] and [CI] !

Comparison of the profiles of the [^{13}CII] hyperfine lines in **Mon R2** with the scaled [^{12}CII] profiles at central position.

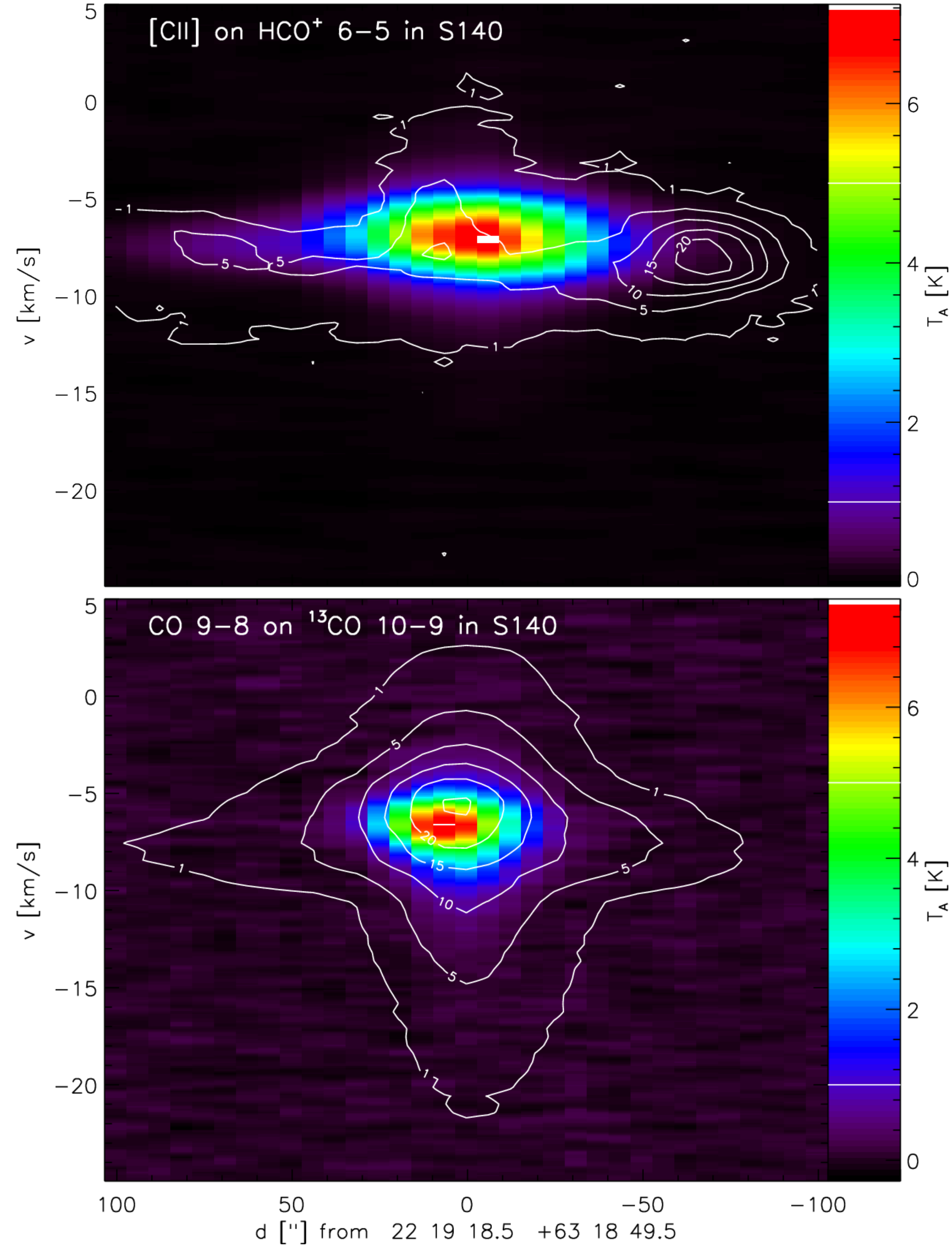




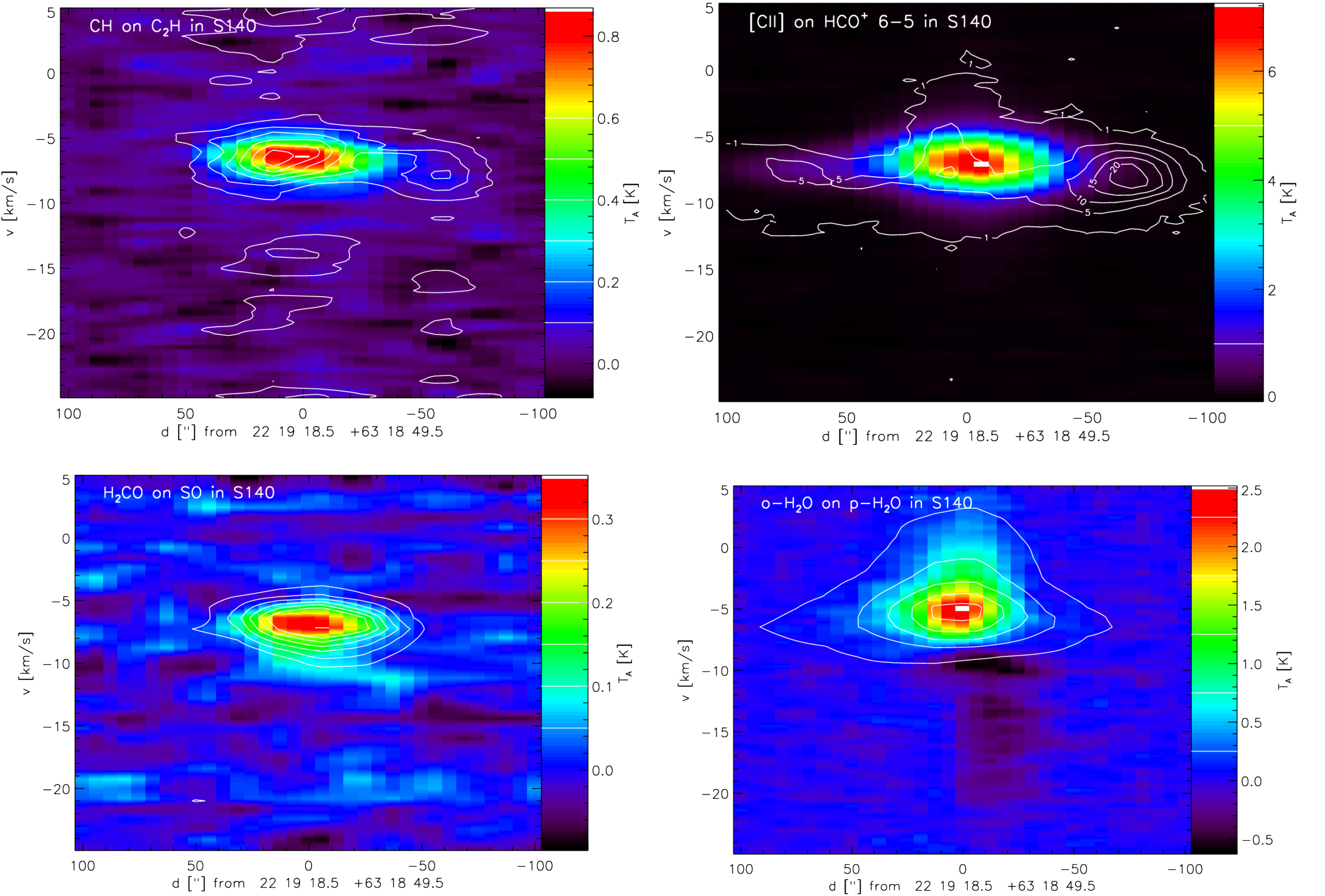
Example 5: S140

External PDR + embedded source IRS1 with internal PDRs:

Observed cuts in S140 overlaid on IRAC 3.6-8μm image



Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: ^{13}CO 10-9 (colors) + CO 9-8 (contours)



Top: C_2H (colors) + CH (contours)
Bottom: SH^+ (colors) + CH^+ (contours)

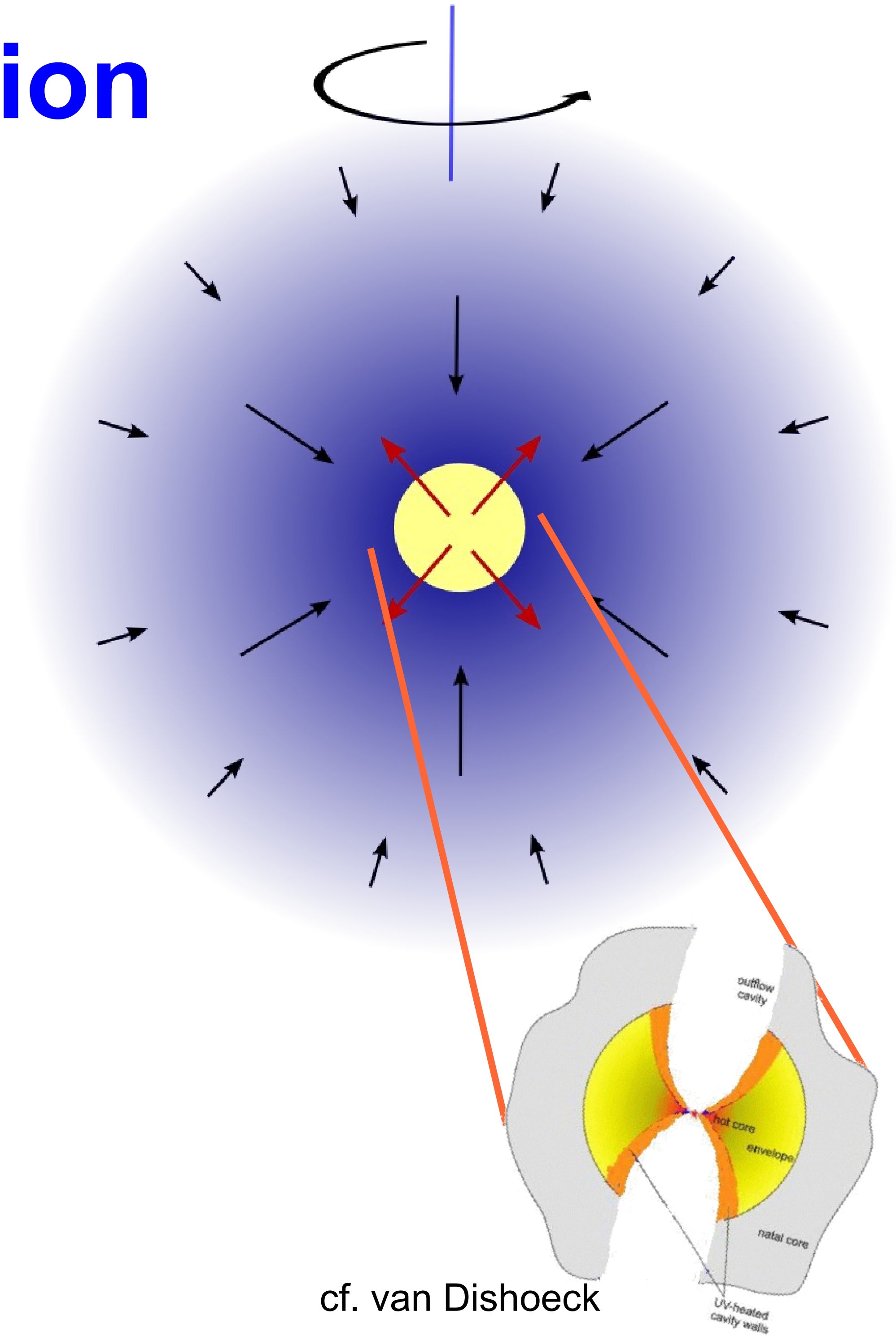
Top: HCO^+ 6-5 (colors) + [CII] (contours).
Bottom: p-H_2O (colors) + o-H_2O (contours)

Interpretation

- Configuration of IRS1 should be similar to Mon R2

- Also broad wings in CO, H_2O
- Same self-absorption pattern in H_2O lines

- But: [CII] is much weaker
  - Only seen from outer PDR
  - HII region still much smaller?
  - [CII] only shows red wing



cf. van Dishoeck

Summary

- Radiation pressure driven PDR dynamics is complex
    - Pressure jump at the surface confirmed
    - Chemical stratification often resolved
        - But inversion possible due to stronger coupling of interclump gas tracers to radiative pressure
        - Line width sequence: [CII]/CH^+ - CH – other molecules
    - Significant dispersion of gas traced
        - Possibly first direct observation of radiative core compression in NGC3603
            - Pillar formation → star-formation triggering ?
    - No evaporation flows!
    - No indication of turbulent stirring through radiation
- More data analysis to come (too many spectra for the models)